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ON THE EFFECT OF TRANSITION ON PARAMETERS WITHIN A SEPARATION REGION AT HYPERSONIC SPEEDS - WITH EMPHASIS ON HEAT TRANSFER [1]

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ABSTRACT

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Previous investigations have indicated that there are many important parameters for separated flow. While these parameters are noted in the literature, a systematic investigation of the various parameters is often lacking. Experimental results of a systematic investigation of the heat transfer in laminar, transitional and turbulent separated regions on a flat plate are presented for a free stream Mach number of 6.0. Included are integrated values of the heat transfer in the separated region and the peak heating on wedges mounted on the plate. In addition, a meaningful analysis (including existing and some new data) of the plateau and first peak pressures has been obtained for separated flow forced by many geometric shapes including steps, wedges, curved corners and secondary jets with exit Mach numbers of 1 to 6. AUTHOR

INTRODUCTION

Flow separation is a common occurrence in aerodynamics that will occur on any surface where the pressure rise and pressure gradient are sufficiently large. Perhaps the two foremost aspects of the separation problem are the resulting pressure and heat transfer effects. A knowledge of the effect of separation on pressure distributions is useful in determining aerodynamic characteristics of controls. Heat transfer data are useful in determing the effect of separation on the aerodynamic heating distribution and the total heat flow into any hypersonic or reentry vehicle. Theoretical predictions of the pressures and heat transfer associated with regions of boundary-layer separation are usually difficult to obtain and often lose much of their validity because of the simplifying assumptions necessary to solve the governing equations. Therefore, the complexity of the flow usually demands that experimental results be utilized to evaluate constants and parameters for the different calculations and to serve as a check on the validity of the prediction. Previous theoretical and experimental investigations (refs. 1 through 11, for example) have indicated that there are many parameters which can be important in establishing and in determining the character of a region of separated flow. While these parameters are noted in the literature, a systematic investigation of the various parameters is often lacking. The effects of separation on heat transfer are not as well documented as those on pressure distributions, particularly at high supersonic and hypersonic speeds.

The purpose of this paper will be to discuss current experimental results for several fundamental systematic separation studies as determined by heat transfer tests conducted on flat plates at Mach numbers of 6.0 in the 20-inch Hypersonic Tunnel Section of the Langley Research Center. In addition, a brief review of separation pressures with some new data at a Mach number of approximately 6 to 8.5 are presented. While the theoretical analysis of the heat transfer data is not complete, the data are presented in the belief that upon proper classification of experimental separation results, enough can be learned to permit a more realistic and meaningful approach to the theoretical analysis of the problem. Also, the data presented should be useful as a guide to other researchers since, with the present state of the art, theoretical analyses may lack generality.

A REVIEW OF PRESSURES ASSOCIATED WITH DIFFERENT TYPES OF SEPARATION

One of the predominant parameters in separated flow is the location of transition relative to the separation point and the flow reattachment point. This has led previously to the classification of separated flow (see, for example, ref. 3) into the following three catagories: (1) pure laminar separation with transition downstream of reattachment, (2) transitional separation with transition occurring at least partially between the separation and reattachment points, and (3) turbulent separation with the end of transition upstream of the separation point. Using these classifications, a meaningful analysis of the plateau and first peak pressures in the separated region has been obtained for separated flow forced by different geometric shapes such as steps, wedges, or curved corners. Experimental indications are that these pressures are nearly independent of the geometry forcing the separation for supersonic and hypersonic flow. A partial summary of existing experimental data and some new data taken on a flat plate are presented in figure 1 for laminar and turbulent separation. Also shown in this figure are equations which predict these pressures reasonably well. Theoretical considerations have suggested the parameters used in these equations; however, in general, experimental data is responsible for the constants and to some extent the form of the equations. For instance, an order of magnitude analysis in reference 3 suggests for laminar flow the following equation

$$C_{p,p} = \frac{K(c_{f,o})^{1/2}}{(M_o^2 - 1)^{1/4}} \tag{1}$$

which is plotted in figure 1(b) with K equal to 2.08 and $2.61/M_o^2$. While using the latter value for K predicts the experimental data reasonably well, it should be remembered that equation 1 is an approximation which does not include all factors associated with the physical mechanisms (see, for example, ref. 2). The values for $C_{f,o}$ used in figure 1 were determined by the Monaghan T prime method (for example, refs. 12 and 14). If turbulent separation is forced by a step whose height is sufficiently large, $C_{p,p}$ values are only a weak function of Reynolds number, therefore, the correlation parameters in figure 1(a) do not include the parameter $C_{f,o}$. It should also be remembered that the pressure rise measured in a separated region are not necessarily those that will cause separation (refs. 4 and 7).

Another illustration of the fact that the first peak pressure in a separated region ($C_{p,p}$) is essentially independent of the geometry forcing separation was obtained in a study of the interaction of secondary jets with the mainstream (ref. 13). Some additional first peak pressure data for a flat plate have resulted from an unpublished study of the effects of secondary jet exit Mach numbers (Mach numbers from 1 to 6) on a Mach 6 mainstream and are shown in figure 2. Figure 2 shows that the first peak pressures in the separated region are essentially independent of jet exit Mach number but increase slightly with increasing jet pressure. The first peak pressures are approximately the same as those of figure 1(a) where turbulent separation was forced by steps, wedges, or curved corners.

HEAT TRANSFER ASSOCIATED WITH DIFFERENT TYPES OF SEPARATION

The models of the present investigation consisted of sharp and blunt leading edge flat plates upon which wedges and steps could be mounted. The heat transfer data was taken by quickly injecting the model from a sheltered position into an established hypersonic free stream. The models were tested in a 20-inch Mach 6 tunnel and a blowdown Mach 6 tunnel which are described in references 6 and 15 respectively. Test conditions and data reduction are similar to those described in reference 17.

As has been noted for pressures, one of the principal variables controlling the heat transfer parameters in a separated region is the type of separation as determined by the position of transition. Figure 3 presents an illustration of the different types of separation. The heating rates for the flat plate with steps are non-dimensionalized with the faired curve of the flat plate values used as a standard. Also presented on the right side of figure 3 are the flat plate heating rates non-dimensionalized by the calculated stagnation values of a one foot radius sphere (ref. 16).

For the case of pure laminar separation (figure 3(a)) the local heating in the separated region are less than those of the flat plate without separation. For transitional separation (figure 3(b)) the local heating rates decrease below the flat plate values until transition occurs and then increase rapidly to values above the flat plate. For turbulent separation (figure 3(c)) the local heating rates increase rapidly upon separation and remain much higher than the flat plate values. Comparison of the lowest heating rate ratio of approximately 0.14 for laminar separation to the maximum value (5.2 obtained for transitional separation) shows considerable dependence upon the type of separation (for the above conditions the local heating rate ratio varies by a factor of approximately 37). However, not too much importance should be attached to the absolute value of this ratio since theoretically the skin friction drops to zero at the separation point (see, for example, ref. 18) and the lowest heat transfer values obtained are probably partially a function of the stability of the flow with time.

One of the more important parameters in heat transfer considerations is the average heat transfer rate in a separated region. Figure 4 shows the integrated heating flow rates over regions of separated flow nondimensionalized by the integrated heating flow rates over the same region on a flat plate at a comparable Reynolds number. The Reynolds numbers shown in this figure are based on conditions at the edge of the boundary layer in undisturbed flow. For the blunt leading edge plate the local flow as assumed to have passed through a normal shock giving a nominal M_o of 3.16. Separation was forced by a forward facing step of heights of .25 or .40 inch located at several longitudinal distances to obtain a wide Reynolds number range.

The data on figure 4 shows definite trends of the average heat transfer rate for the different types of separation. Within the area representing the laminar separation data the heating rate has an approximately constant value of 0.52 which compares very well with the prediction of 0.56 for separated flow over a cavity given by Chapman in reference 11. (An approximate correction to these experimental values to account for the pressure rise due to separation would be to divide these values by $\sqrt{p_w/p_o}$ as discussed in reference 14. However, it would make only a small difference for these particular cases since the value of $\sqrt{p_w/p_o}$ is only about ten percent above unity.) Within the area of the figure representing the transitional separation data the heating rate increases rapidly with increasing Reynolds number from the average laminar values of 0.52 to a peak value of at least 2.5. For the area of the figure representing the turbulent separation data, the heating rate appears to level off and then decrease with increasing Reynolds number.

Examples of the Stanton number distribution obtained on a flat plate with wedges are shown in figure 5. The flat plate laminar heat transfer parameter, $N_{St}\sqrt{R_{oo,x}}$ is plotted against surface distance from the leading edge. Also included are curves which show the faired data obtained on the flat plate without a wedge. When the flow is laminar and not separated, the correlation parameter $N_{St}\sqrt{R_{\infty,x}}$ approaches a near constant value on the plate which is approximately equal to the theoretical value shown on the left of the figure (see ref. 14 for calculation method). Again the experimental values in the separated region ahead of the wedge are below or above the flat plate values depending upon the position of transition. The analysis of the data in this figure is further complicated by the fact that when the flow near the junction of the wedge and flat plate becomes transitional separation does not occur for the 20° wedge. (Separation occurs for all wedge data shown in figure 5 except when $R_{\infty} > 4 \times 10^6$ for the sharp leading edge plate with a 20° wedge.) The experimental data show a large variation in the local and maximum values and the location of these maximum values along the wedge as the position of transition changes.

A very important parameter for a configuration of this type is the peak heating rates which occur on the wedges. It has a practical application in that winged reentry vehicles which are nearly flat with trailing edge controls demand a knowledge of the maximum heating on the surface. Figure 6 presents the peak local heating obtained on the surface of wedges at various angles in the form of Stanton number versus free stream Reynolds number based on distance of the wedge from leading edge. Also included in the figures for comparison only are the Stanton numbers calculated by the equation $N_{St} = N_{St_{\alpha=0}} k_3\sqrt{p_w/p_{\alpha=0}}$ which gives the approximate Stanton numbers on a flat plate at various angles of attack for laminar flow (see ref. 14). The value of k_3 is taken as unity and $p_w/p_{\alpha=0}$ is the theoretical inviscid two dimensional value. Transition apparently has occurred or is occurring at the reattachment point for all data shown in the figure except the 10° wedge data at the lower Reynolds numbers. In general the data indicates that the peak heating for any given wedge would increase markedly as the reattached flow becomes transitional (see 10° wedge) and at some higher Reynolds number would begin to decrease. The peak heating on a 30° wedge was at least 40 times greater than the heating rate on the sharp leading edge flat plate upon which the wedge was placed. In general, the peak heating on a wedge compared to the plate was greater for the sharp leading edge plate than for the blunt leading edge plate. This is in agreement with the data of reference 19 where it was found that the peak heating for a protruding distortion on a plate was a function of local Mach number at the edge of the boundary layer.

Another current study with practical application in hypersonic flight is the investigation of the effect of lateral cavities on boundary layer transition downstream of the cavity. Some preliminary results of this study are presented in figure 7 where the heating rate for several cavity widths are given. For one leading edge thickness and angle of attack, transition was unexpectedly delayed approximately two inches by all the cavity widths tested (figure 7(a)). However, for other leading edge thickness with the plate at only slightly different angles of attack, transition was either uneffected or promoted as expected. While the preliminary data presented in figure 7 is not fully understood, it does suggest that an interaction effect exists between transition and separation which should be further investigated as a possible method of reducing the heating rates on reentry vehicles. It is speculated from these tests that under certain conditions separation can delay transition. Another probable example of this phenomenon occurred in reference 17 where it is shown that small three-dimensional roughness on a flat plate with a sharp leading edge can under certain conditions slightly delay transition. This speculation also agrees with the data in reference 3 where it is shown that the stability of a separated laminar mixing layer increases more rapidly with Mach number than does the stability of an attached laminar boundary layer.

CONCLUDING REMARKS

Separated flow has previously been classified as pure laminar, transitional, or turbulent separation. Using these classifications, a meaningful analysis of the plateau and first peak pressures has been obtained for separated flow forced by many geometric shapes including steps, wedges, curved corners and secondary jets (exit Mach number of 1-6).

Results of a systematic study of the heat transfer in laminar, transitional and turbulent separation regions on a flat plate has been presented for a Mach number of 6.0. While the theoretical analysis of the heat transfer data is not complete, analysis of the experimental data has indicated results and trends which should make possible a more realistic and meaningful approach for a theoretical consideration of the problem. Some observations from this study are given below. The local heating rates in the separated region or the peak heating rates on wedges vary considerably depending upon the position of transition. The ratio of average heating rate in a separated region to the same region with attached flow can vary from approximately .5 for laminar separation to 2 or greater for transitional or turbulent separation. Heat transfer studies behind cavities have indicated that there is an interaction between separation and transition and that under certain conditions the cavities can delay transition (cavities can also promote transition under certain other conditions).

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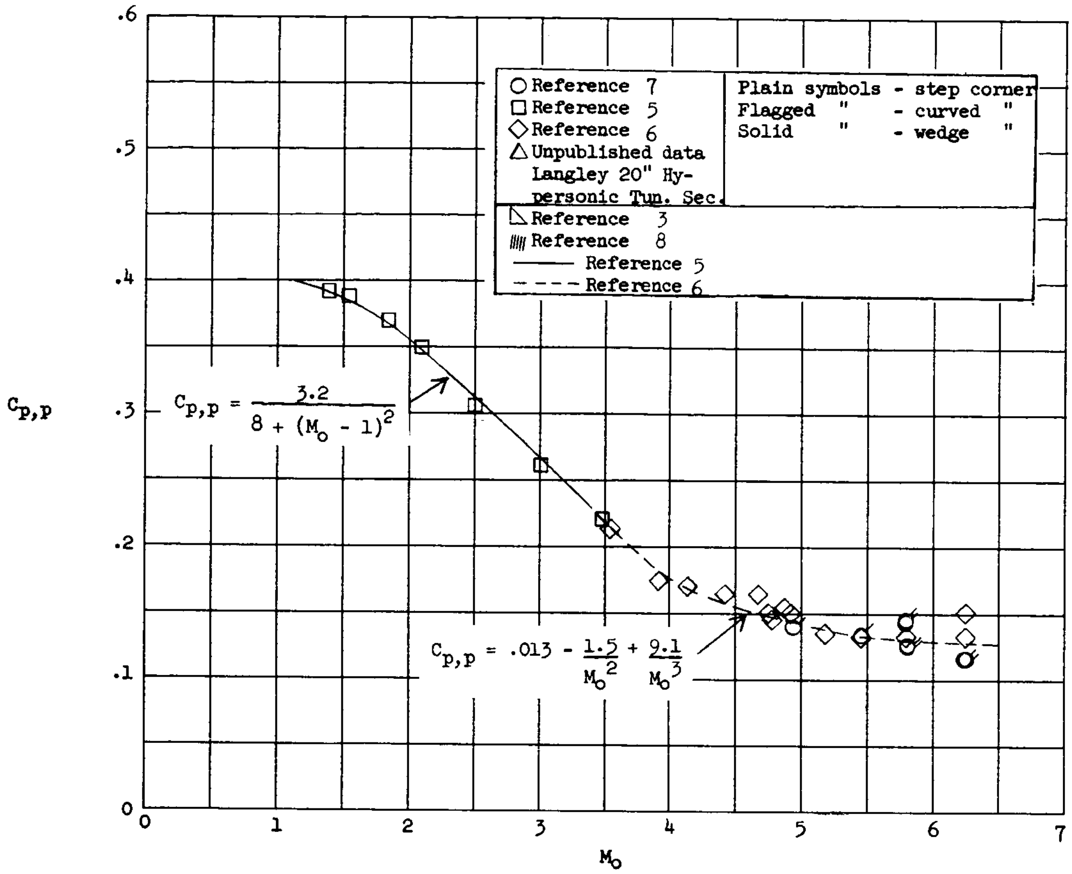
NOMENCLATURE

C_f	local skin-friction coefficient
C_p	pressure coefficient $\frac{p-p_o}{q_o}$
k_3	correction function in heating rate equation due to pressure gradient (see ref. 14)
K	factor in equation 1
M	Mach number
N_{St}	Stanton number based on free stream conditions assuming a laminar boundary layer
p	pressure
$\dot{q}$	experimental heat transfer rate
$\dot{q}_t$	stagnation heating rate calculated for a one foot radius sphere (ref. 16)
R	Reynolds number
t	average diameter of leading edge, inches
T	temperature
x	distance along plate measured from leading edge
α	angle of attack, positive values indicate a compression on surface
δ	angle that wedge makes with flat plate

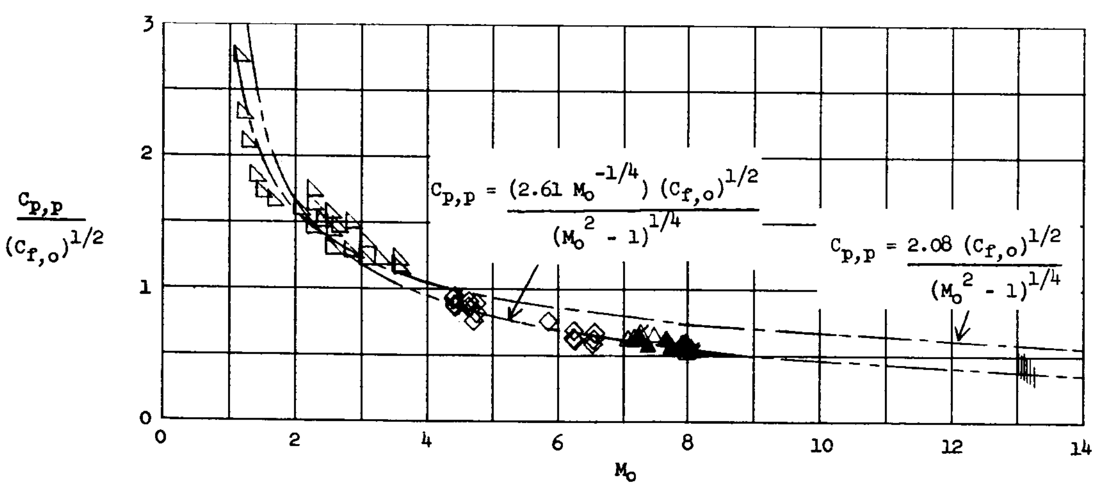
Subscripts:

1	beginning of separation
2	reattachment location
∞	free stream
c	conditions with cavity on plate
fp	flat plate conditions

j	jet conditions at exit
max	maximum
o	undisturbed conditions ahead of pressure rise at outer edge of boundary layer
p	plateau conditions for laminar separation, or first peak condition for turbulent flow
s	conditions with step on plate
w	wall
x	distance along plate measured from leading edge
x'	distance along plate from leading edge to beginning of wedge or step



(a) Turbulent.



(b) Laminar.

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Figure 1.- Variation of separation-pressure parameters with Mach number.

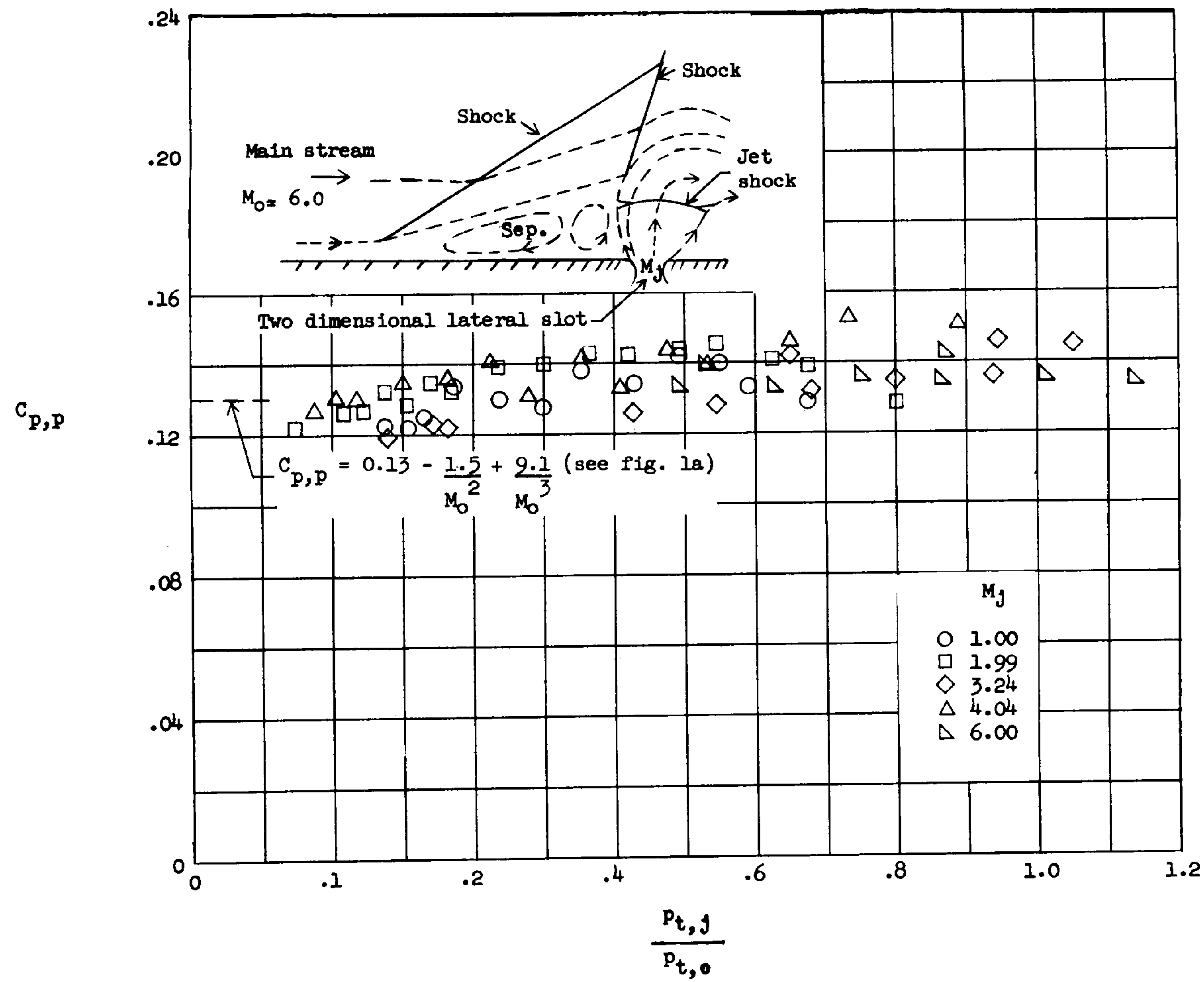

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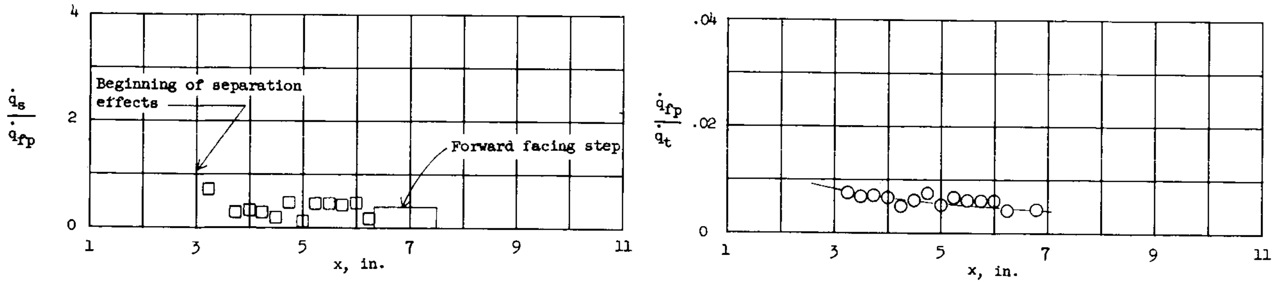
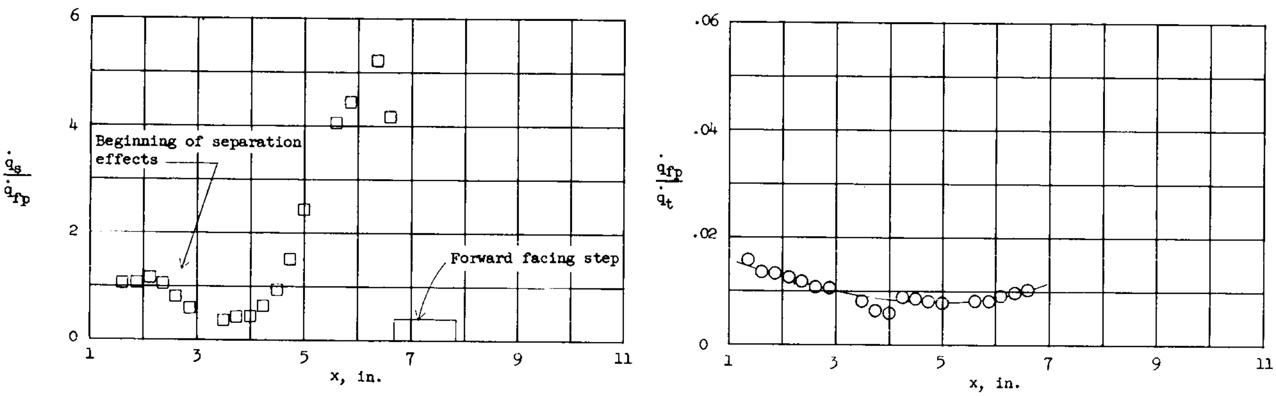
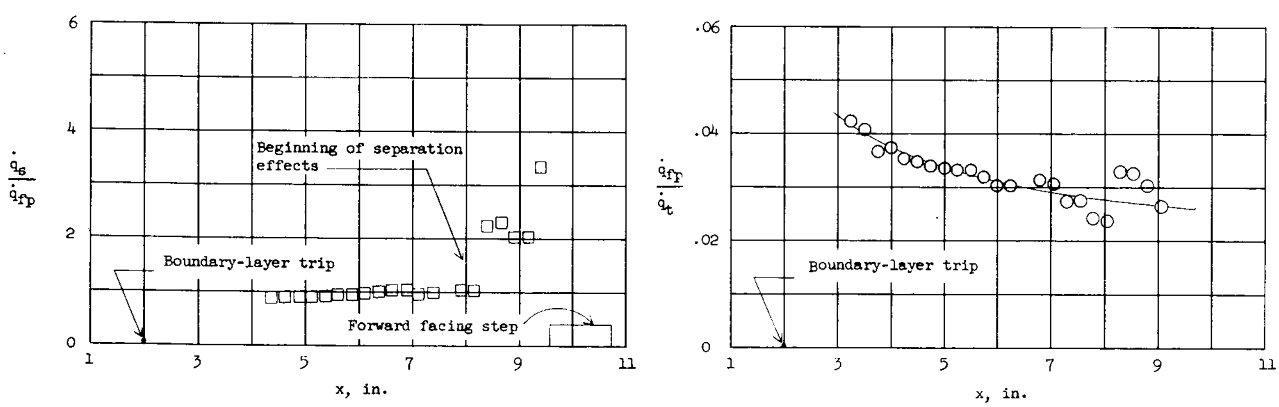
Figure 2.- First peak separation pressure for turbulent separation forced by secondary jets with various Mach numbers and pressure ratios.



(a) Laminar separation, $R_\infty = 1.2 \times 10^6$ per foot.



(b) Transitional separation, $R_\infty = 5.5 \times 10^6$ per foot.



(c) Turbulent separation, $R_\infty = 7.8 \times 10^6$ per foot.

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Figure 3.- Heating rate distributions for three types of separated flow caused by a forward-facing step. $t = 0.0015$ inch; $M_\infty = 6$.

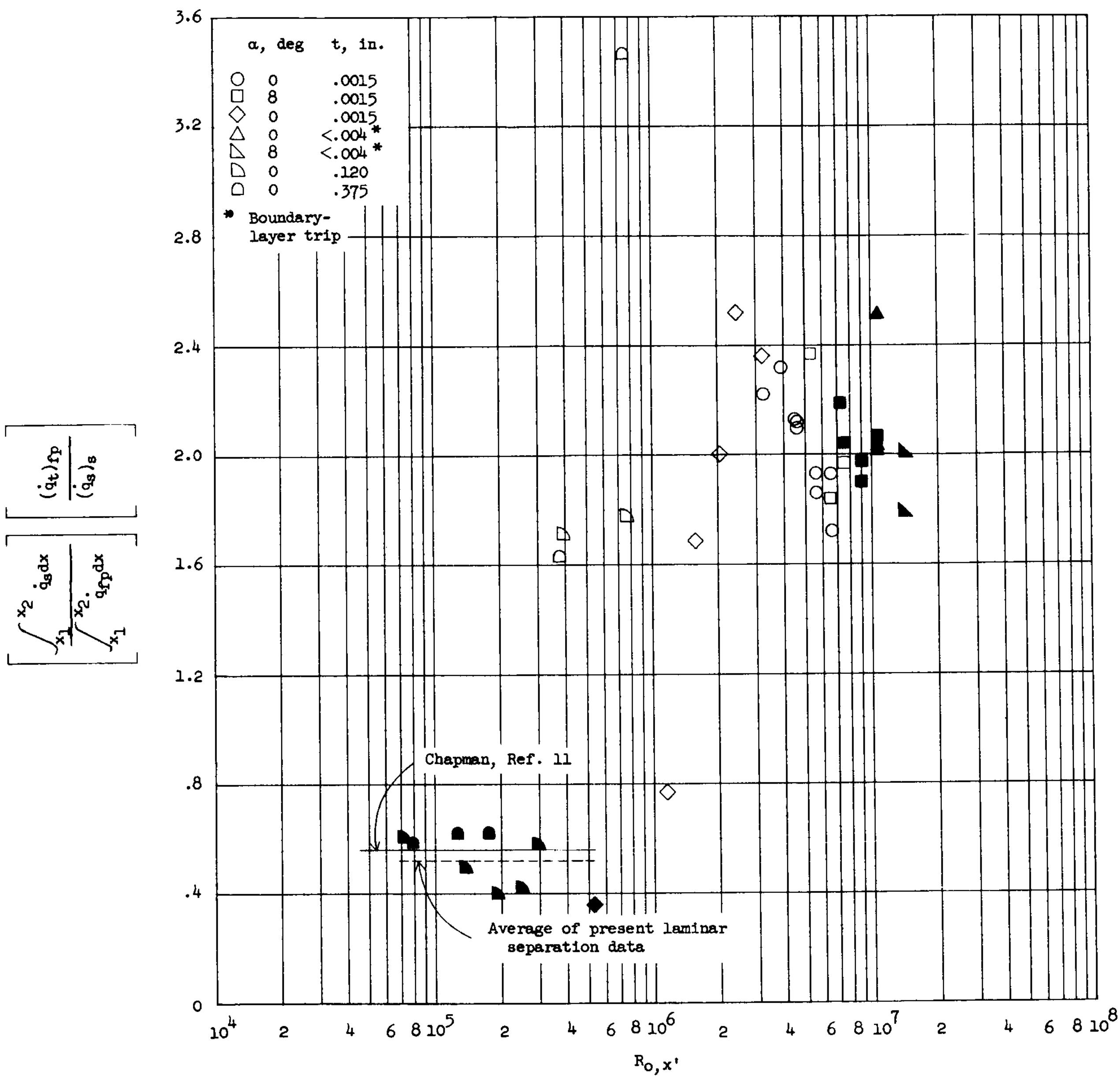

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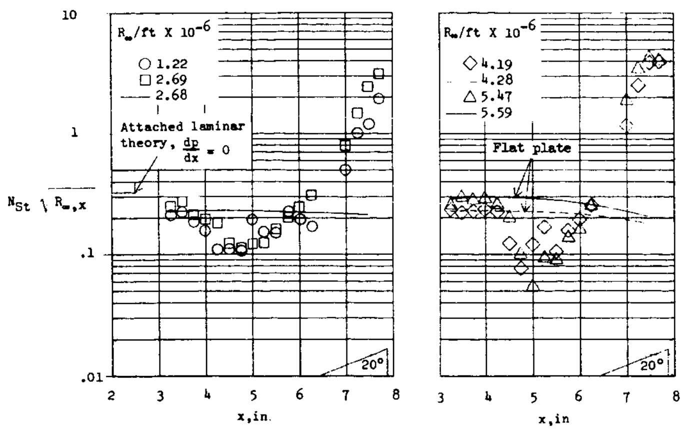
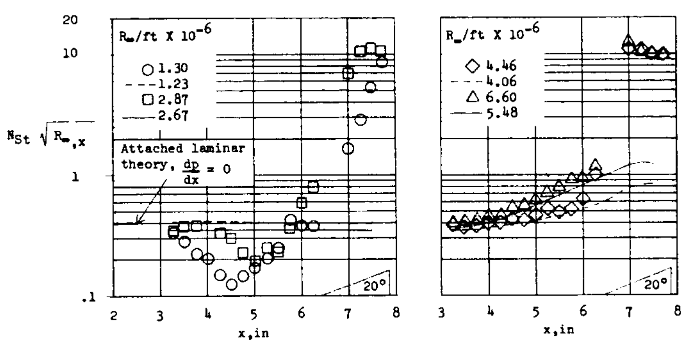
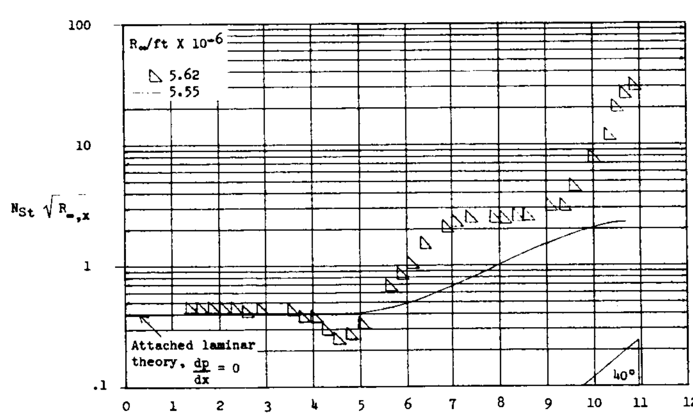
Figure 4.- Ratio of average heating rate for region of separation to same region for flat plate without separation at several Reynolds numbers and a M_∞ of 6.0. (Solid symbols on left of figure denote pure laminar separation, open symbols denote transitional separation, and solid symbols on right denote turbulent separation.)



(a) 20° wedge, blunt leading edge, $t = 0.120$ inch.

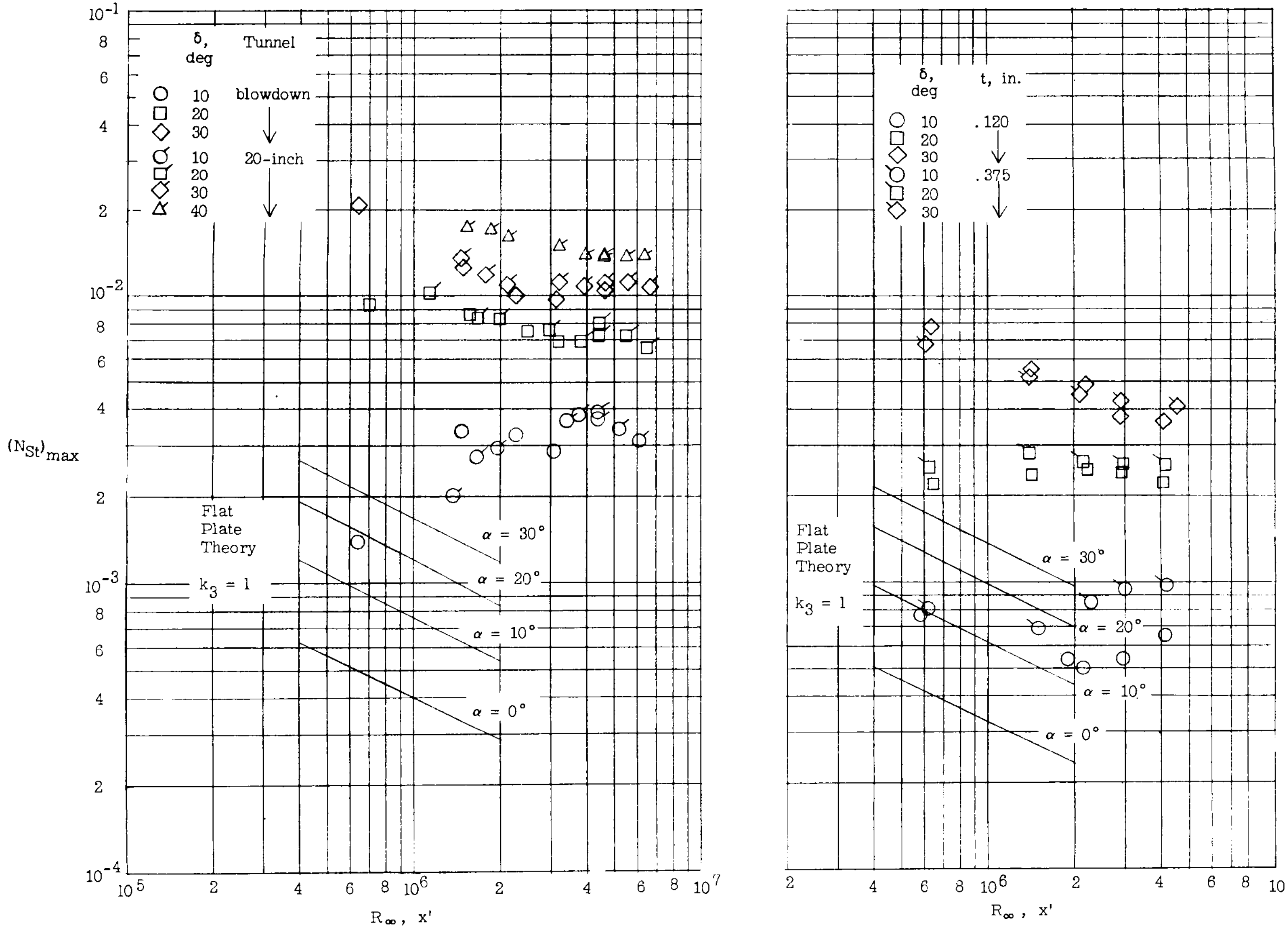


(b) 20° wedge, sharp leading edge, $t = 0.0015$ inch.



(c) 40° wedge, sharp leading edge, $t = 0.0015$ inch. NASA

Figure 5.- Local heat-transfer parameters on a flat plate with wedges for various Reynolds numbers. $M_{\infty} = 6.0$.



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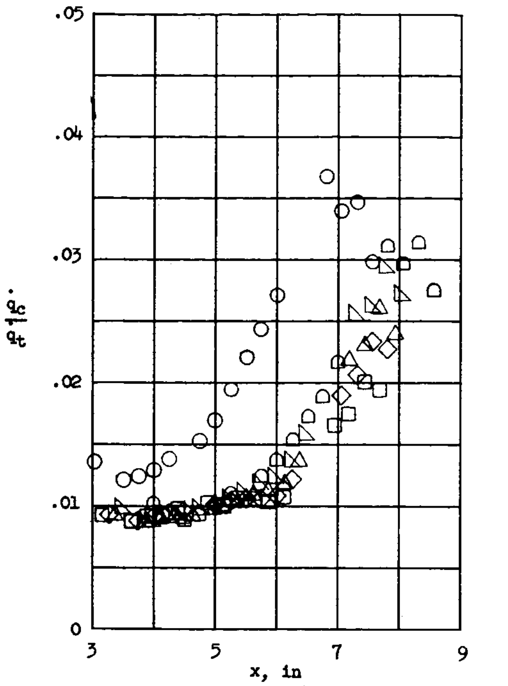
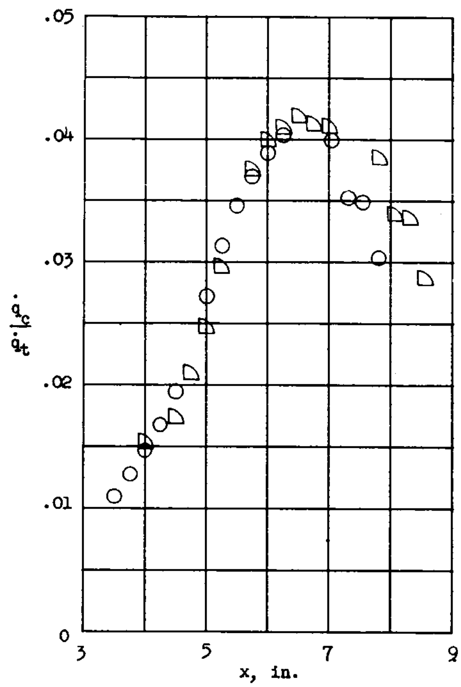
(a) Sharp leading edge, $t = 0.0015$ inch. (b) Blunt leading edge, blowdown tunnel.

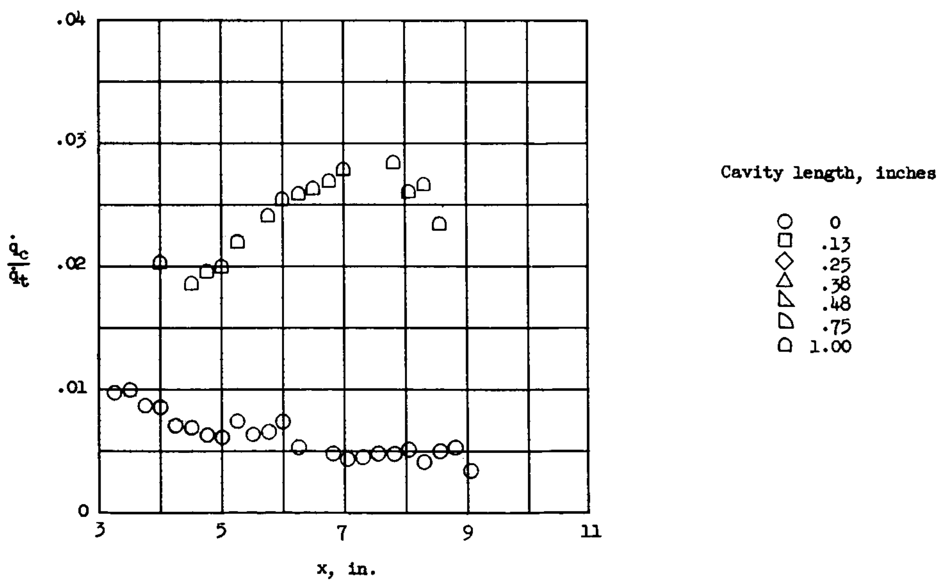
Figure 6.- Maximum Stanton number on wedge variation with free-stream Reynolds number for various wedge angles at $M_\infty = 6.0$.



(a) t = 0.0025 inch; α = -35 feet; x_c = 2.65 inches.



(b) t = 0.0015 inch; α = 9 feet; x_c = 2.90 inches.



(c) t = 0.120 inch; α = 9 feet; x_c = 2.65 inches.

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Figure 7.- Effect of lateral cavities on boundary-layer transition. $M_\infty = 6.0$ and $R_\infty \approx 8 \times 10^6$ per foot (cavity depth = 0.375 inch).

NASA-Langley, 1963